AD-A129 378 DURABILITY OF PROPELLER SHAFT INTERFERENCE FITS UNDER VARIABLE CYCLIC LOADING(U) DEFENCE RESEARCH INFORMATION CENTRE ORPINGTON (ENGLAND) A S FEDOROV ET AL. MAY 83 1/1

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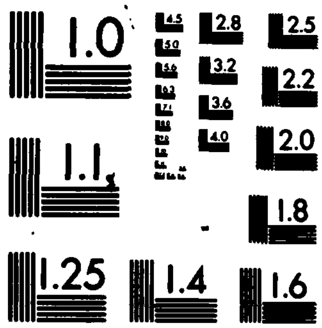

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DURABILITY OF PROPELLER SHAFT INTERFERENCE FITS UNDER VARIABLE CYCLIC LOADING

A.S. Fedorov, [illegible].M. Pasumanskii and [illegible].V. Birulya

Sudostroenie (Shipbuilding), 1977 (6), 22 - 25.
(Translated from Russian)

The durability of propeller shafts of ships with large tonnage governs their strength under the action of cyclic bending stresses arising under variable operating conditions. The relative number of overload cycles with an amplitude greater than the durability limit of the material from which the shaft is made, required to bring about failure (σ_{-1}) is estimated to be less than 1% of the total number of loading cycles. Overloading occurs basically when the ship travels during a storm, and is to be explained by exposure of the propeller blades (to the air) during rolling and also as a result of irregular variations in the water velocity field in the propeller disc. Even a small number of overload cycles may, however, prove dangerous for the durability of the propeller shaft, since a large portion of the cycles of the operational load gives rise to stresses exceeding the limit of resistance to crack formation σ_{-1}.

Calculation of the durability of propeller shafts is complicated by the fact that virtually no studies have so far been carried out on fatigue phenomena in press fits subjected to the action of variable loads. In connection with this, an experimental study of durability under variable cyclic bending stresses was carried out on a model of a propeller shaft with 50 mm diameter and with pressed on propeller boss.

The influence of the basic parameters of the variable load on the durability of the test specimens was studied using a known criterion, the relative durability:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} \quad \text{(subsequently abbreviated to } \sum \frac{n}{N}\text{)}$$

where n_i is the number of operating cycles σ_i to failure in a test under variable conditions;

N_i is the number of cycles to failure in a test under steady conditions applying a stress of σ_i;

k is the number of stress amplitude levels greater than σ_{-1} in the variable test.

Test specimens were prepared from normalising carbon steel type 35 (σ_v = 55 kgf/mm^2, σ_g = 28 kgf/mm^2, a_n = 6.7 kgf . m/cm^2), frequently used in the production of ship's propeller shafts. Propeller boss material : type 45 steel; after hardening and tempering : HB 220 - 240. The external diameter of the propeller boss pressed on to the specimen was 100 mm; the conicity of the end part of the specimen and the propeller boss opening was 1 : 20; the length of the mating taper portions was 100 mm. The specimens were of a symmetrical double-ended construction, two conical interference fits were used simultaneously. The conical surfaces of the specimen and of the propeller boss were finished by polishing and checked for roughness on a dye gauge R_z = 3.2 to 6.3 mcm. The mean contact pressure in the fit, calculated using Lamé's formula, was p = 8 kgf/mm^2.

The tests were carried out on a clean plain cylindrical anvil with the aid of an electromagnetic resonance type apparatus. As the nominal amplitude of the bending stresses applied during the test, we used its value in the mean cross section, located at a distance of at least twice the diameter of the test specimen from the end face of the propeller boss pressed on it.

In the first stage of the investigation (test series I), we derived the durability curve under a constant cyclic load. The test was conducted on 16 test specimens at 5 stress amplitude levels. All fractures of the specimens appeared in a section lying close to the end face of the propeller boss. The results of the tests under steady conditions are shown in Fig. 1 (points 1). Statistical processing of these results gave the following equation for the experimental durability curve : $N\sigma^{5.44} = 10^{12.82}$ and 80% confidence limits 4 of the mean durability curve (Fig. 1).

Extrapolating, while taking into account data obtained with other test specimens of interference fits (cf. points 2, Fig. 1), we find that the durability limit based on 50 million cycles is $\sigma_{-1} \approx 11$ kgf/mm^2.

A specimen tested at a stress amplitude $\sigma = 10$ kgf/mm^2, which had not fractured during the course of 30 million cycles, developed fatigue cracks with depths up to 0.5 mm, distributed over the surface in the region of the end face of the hub.

Specimens of the series II - XI were tested under variable loading conditions. The load was applied in the form of repeating programmed blocks, the parameters of which were varied within the limits indicated in the table. The influence of the individual parameters can be adjudged more readily by grouping series of tests. Series IV, VI and VIII, and V and VII show the influence of the value of σ_{min} on the durability of the specimens at values of $t_{\sigma_{max}} = 0.01$ and 0.0014. The lower amplitude limit of streses giving rise to damage at a test based on 10^8 cycles lies at $\sigma_{min} \approx (0.6 - 0.7)\sigma_{-1} \approx \sigma_{-1cr}$. Evidently, the result also holds for a case in which the durability extends to 10^9 cycles, which corresponds to the load to which the shafting of a freighter is subjected during a period of 25 - 30 years. If it is necessary to design details of interference fits for a durability in excess of 10^9 cycles, the lower limit of damage-

producing stresses must be defined more accurately.

When the value of σ_{min} is increased to $(0.8 - 1.0)\sigma_{-1}$, these stresses exert a stronger damaging action. The relative durability drops to a value of about 0.3 - 0.6 under these conditions, which corresponds to a 2- to 3-fold deviation of damage produced from the linear law of summation, with a reduced margin of durability.

In the tests we did not observe any significant differences in the values of $\sum \frac{n}{N}$ between $\sigma_{min} = 0.8\ \sigma_{-1}$ and $1.0\ \sigma_{-1}$. According to S.V. Serensen (? Sörensen) this phenomenon is to be explained by the fact that beforehand exposure of the specimens to stresses equal to the durability limit, may exert an even stronger action, leading to an increase in the durability during the subsequent changeover to stresses $\sigma_i > \sigma_{-1}$.

The results of the tests of series II - VII make it possible to gauge the influence of another important parameter, the relative number of cycles of the action of stress with maximum amplitude $t_{\sigma_{max}}$ on the relative durability $\sum \frac{n}{N}$. A lowering of $t_{\sigma_{max}}$ results in an increase in the number of cycles of the action of stress at the minimum level $n_{\sigma_{min}}$ to failure, which leads to an increase in the proportion of fatigue damage caused by their action.

The difference in the values of $\sum \frac{n}{N}$ corresponding to $t_{\sigma_{max}} = 0.01$ and 0.0014 respectively appeared at first sight to be unexpectedly small. The reason for this lies in the fact that the level of σ_{max} was increased in series V and VII in order to prevent an increase in the durability in the experiments due to a lowering of $t_{\sigma_{max}}$ to 0.0014. The combinations of $t_{\sigma_{max}}$ and σ_{max} in series VI and V, and VI and VII were such that the duration of the tests and hence the number of cycles of stress application σ_{min} were approximately equal. Consequently, fatigue damage due to the

action of the stresses σ_{min} was identical, resulting in approximately equal values of $\sum \frac{n}{N}$.

It is of interest to conduct an analysis of the effect of stresses at the minimum level in the tests of the series II - V (σ_{min} = 0.8 σ_{-1}, t_{max} = 0.4, 0.1, 0.01, 0.0014) using another criterion, the magnitude of the specific damage $q_{\sigma_{min}}$, i.e. damage due to one stress cycle σ_{min}:

$$q_{\sigma_{min}} = \frac{1 - \sum \frac{n}{N}}{n_{\sigma_{min}}}, \qquad (1)$$

where $n_{\sigma_{min}}$ is the number of stress cycles σ_{min} to break in the variable stress tests; the quantity $q_{\sigma_{min}} n_{\sigma_{min}}$ corresponds to the proportion of damage due to the stresses σ_{min}.

The analysis shows that the values of $q_{\sigma_{min}}$ obtained in tests based on 10^8 cycles, i.e. for $t_{\sigma_{max}}$ = 0.01 and 0.014, are the most reliable ones. This is bound up with the fact that the error inherent in the calculation of $q_{\sigma_{min}}$ due to the error in the determination of the durability N in the tests under steady stress conditions, decreases with an increase in the duration of the variable load test. Therefore, we subsequently make use of the values of $q_{\sigma_{min}}$ determined in tests with $t_{\sigma_{max}}$ = 0.01 and 0.0014. Fig. 2 illustrates the values of $q_{\sigma_{min}}$ corresponding to σ_{min} = 7, 8.7 and 11 kgf/mm^2, and those obtained in the tests under steady conditions for values of $q_{\sigma_i > \sigma_{-1}} = \frac{1}{N_i}$. The observed trend of the dependence of the specific damage on the stress amplitude σ_i in the range from (0.6 - 0.7)σ_{-1} to 2.2 σ_{-1} enables us to express the number of cycles to break n under conditions of variable stress by the following equation

$$n \Sigma t_{\sigma_i} q_{\sigma_i} = 1, \qquad (2)$$

where t_{σ_i} is the relative number of cycles of the application of stress σ_i, under variable conditions;

q_{σ_i} is the specific damage due to the action of the stress σ_i ($q_{\sigma_i > \sigma_{-1}}$ is determined in tests under steady conditions and $q_{\sigma_i \leq \sigma_{-1}}$ in variable tests based on a large number of cycles).

Deriving equation (2) which agrees with known expressions for linear summation of the damage $\sum \frac{n}{N} = 1$ and differs from the latter in that, owing to the change in $1/N_i$ by q_{σ_i}, it is possible to study the damaging effect of smaller durability limits. It is assumed that the absence of an effect on q_{σ_i} at the other levels of σ_i, the latter is confirmed by an analysis of the values of $q_{\sigma_{min}}$, obtained in the tests of the series IV - VII, in which there was no effect of the level of σ_{max} on $q_{\sigma_{min}}$ (Fig. 3). Transition from the level $\sigma_{max} = 1.65\ \sigma_{-1}$ to $\sigma_{max} = 2.2\ \sigma_{-1}$ leads to some lowering of the value of $q_{0.8\ \sigma_{-1}}$ but an increase in $q_{\sigma_{-1}}$. Taking into consideration the fact the large random scatter of results, these changes in $q_{\sigma_{min}}$ cannot be regarded as significant.

In series IX, X and XI we studied the influence of the number of cycles in the programmed block N_b on $\sum \frac{n}{N}$. In the tests of series IX and X the composition of the load spectra of the stresses was practically the same. The load applied in series XI differed by a significantly smaller relative number of stressing cycles $\sigma_i < \sigma_{-1}$ and their lower amplitude level. Fig. 4 gives information about the magnitude and nature of the loads. It also shows the results of tests which indicate somewhat lower values of $\sum \frac{n}{N}$ in series IX as compared with those of series X. Statistical analysis confirms this lowering at the 0.10 confidence level. The mean value 0.75 of the relative durability, obtained in test series XI, shows that the reduction in the durability of a propeller shaft under actual operational conditions which is determined by frequent variations in the

magnitude of the variable load also must not be significant. The results of the tests of series X also show that the number of stress amplitude levels in one programmed load block does not affect the relative durability.

Thus, calculation of the durability under variable loads is carried out using equation (2).

The results given in the table show that there is only an insignificant difference between calculated and experimental values. In the calculations we used the values $q_{0.8\sigma_{-1}} = 0.58 \times 10^{-8}$ and $q_{\sigma_{-1}} = 0.68 \times 10^{-8}$, obtained as logarithmic means in the tests of series IV - VII.

In the absence of results of tests under variable conditions, information about $q_{\sigma_i < \sigma_{-1}}$, necessary for calculating the durability of interference fits under conditions of variable cyclic loading, may be obtained by extrapolating the durability curve in the region of stresses with a lower durability limit to values of $\sigma_i \approx (0.6 - 0.7)\ \sigma_{-1}$. Fig. 1 shows in addition to the results of tests under steady conditions, the relative durabilities corresponding to stresses below σ_{-1}, determined in the tests under variable stress conditions of series IV - VIII, as $1/q_{\sigma_i}$ (points 3). The method of extrapolation is less accurate but the calculation error lies within the durability margin.

Conclusions

On the basis of the results examined here, applicable to non-secured running of shafts made from carbon steel, the following conclusions may be drawn.

1. The lower amplitude limit of damaging stresses is represented by stresses $\sigma \approx (0.6 - 0.7)\, \sigma_{-1}$.

2. Durability up to 10^9 cycles may be described by the expression $n_\Sigma = (\sum q_{\sigma_i} t_{\sigma_i})^{-1}$, where $q_{\sigma_i} > \sigma_{-1}$, is determined in the tests under steady conditions and $q_{\sigma_i} \leq \sigma_{-1}$ under cyclic loading in 10^8 cycle tests.

3. The number of cycles in one programmed loading block exerts only an insignificant influence on the relative durability.

4. The number of stress amplitude levels in programmed loading does not affect the relative durability.

Basic parameters and results of tests under variable loading cycles conducted on models of propeller shafts with interference fits

Number of test series (No. of test specimens)	σ_{max} (kgf/mm^2)	$\frac{\sigma_{max}}{\sigma_{-1}}$	σ_{min} (kgf/mm^2)	$\frac{\sigma_{min}}{\sigma_{-1}}$	Number of stress levels	$t_{\sigma_{max}}$	No. of cycles in loading block (N_b)	$\overline{\sum \frac{n}{N}}$	$\bar{n}_{\Sigma,\phi}$ (*) (10^6 cycles)	n_{Σ} (10^6 cycles)
II (3)	18	1.65	8.7	0.8	2	0.4	$1.08 \cdot 10^5$	0.83	2.1	2.4
III (3)	18	1.65	8.7	0.8	2	0.1	$6.5 \cdot 10^5$	0.87	8.6	9.3
IV (2)	18	1.65	8.7	0.8	2	0.01	$21.6 \cdot 10^5$	0.54	54	62.5
V (2)	24	2.2	8.7	0.8	2	0.0014	$21.6 \cdot 10^5$	0.64	87	75
VI (3)	18	1.65	11	1.0	2	0.01	$21.6 \cdot 10^5$	0.69	102	60
VII (2)	24	2.2	11	1.0	2	0.0014	$21.6 \cdot 10^5$	0.31	45	72
VIII (2)	19	1.55	7	0.65	2	0.01	$21.6 \cdot 10^5$	1.11	109	98
IX (4)	21.5	1.95	6.0–8.5	0.55–0.8	Continuous spectrum	0.31	1400	0.73	-	-
X (4)	21.5	1.95	9.7	0.9	9	0.31	$1.08 \cdot 10^5$	1.01	-	-
XI (2)	21.5	1.95	6.0–8.5	0.55–0.8	Continuous spectrum	0.5	300	0.75	-	-

(*) $\bar{n}_{\Sigma,\phi}$ and n_{Σ} are the actual (experimental) and calculated (from equation (2)) numbers of cycles to failure in testing under variable cyclic loading.

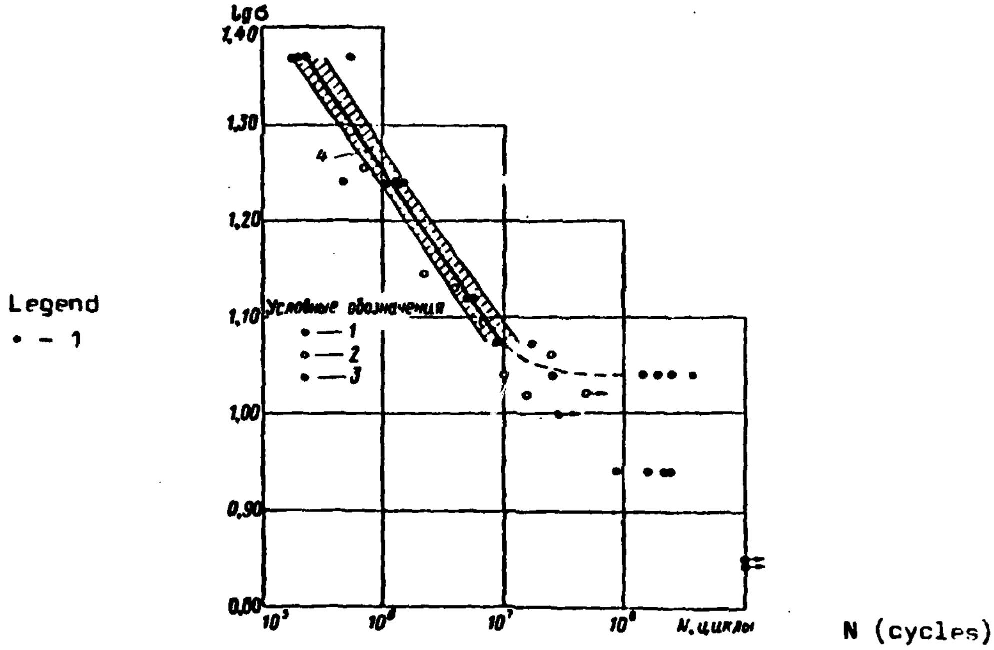

Fig. 1: Results of cyclic bending tests conducted on a model of a propeller shaft with press-on propeller boss.

1, 2 - tests under steady conditions; 3. - nominal durability, determined in tests under variable conditions as 1/q (where q is the value of the specific damage); 4. - region of 80% confidence limit.

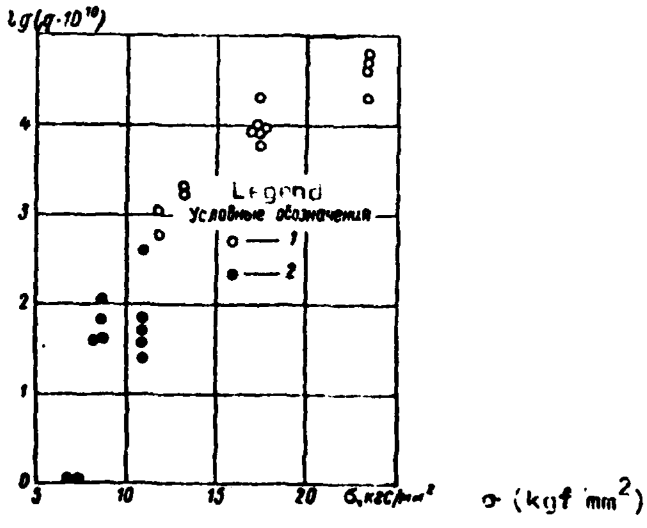

Fig. 2: Specific damage (q) vs. amplitude of cyclic bending stress (σ). 1 - steady conditions; 2 - variable conditions.

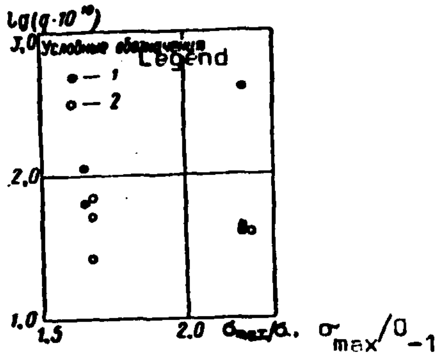

Fig. 3: Influence of the maximum values of the stress amplitude (σ_{max}) in double-level variable tests on the specific damage ($q_{\sigma_{min}}$).

1. Series IV and V - $\sigma_{min} = 0.8\sigma_{-1}$;

2. Series VI and VIII, - $\sigma_{min} = \sigma_{-1}$.

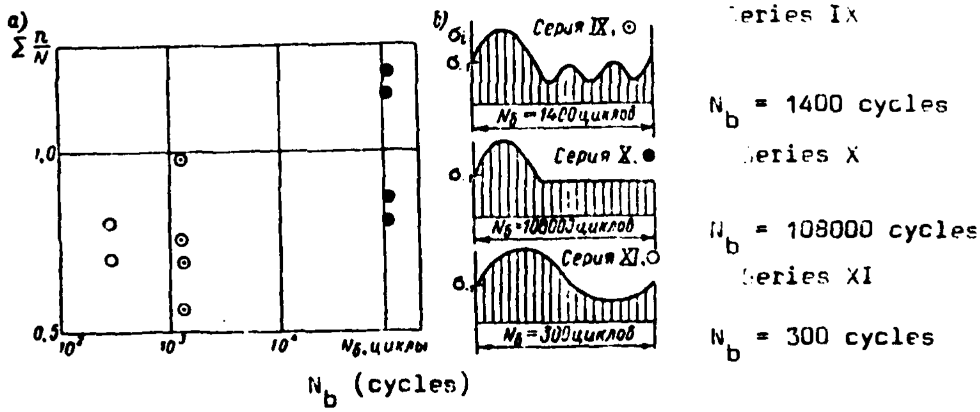

Fig. 4: Influence of the number of cycles in the programmed loading block N_b on the relative durability $\sum \frac{n}{N}$ (a) and the form of the loading blocks (b).

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		DRIC-T-6880	[redacted]

5. Originator's Code (if known)	6. Originator (Corporate Author) Name and Location
9999000N	SUDOSTROENIE No.6, (1977) 22 - 25
5a. Sponsoring Agency's Code (if known)	**6a. Sponsoring Agency (Contract Authority) Name and Location**
7221000N	Procurement Exec., Min.of Defence Defence Res.Info.Centre, UK.

7. Title

DURABILITY OF PROPELLER SHAFT INTERFERENCE FITS
UNDER VARIABLE CYCLIC LOADING.

7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers). Title, place and date of conference

8. Author 1. Surname, initials	9a Author 2	9b Authors 3, 4...	10. Date	pp	ref
Fedorov, A.S.	Pasumanskii,E.M	et al	5.1983	11	0

11. Contract Number	12. Period	13. Project	14. Other References

15. Distribution statement

15. Descriptors (or keywords)

*Propeller shafts, *Life (durability), Fatigue strength at N cycles, Model tests, Bending stress, Cyclic loads.

continue on separate piece of paper if necessary

Abstract Determination of the durability of propeller shafts is complicated by the lack of knowledge of fatigue phenomena in interference fits subjected to variable loads. In view of this experimental studies were carried out on a model propeller shaft under varying cyclic bending stresses. An expression is derived for durability up to 1000 million cycles for carbon steel shafts.

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